Faculty of Electrical Engineering Technology

HYBRID STATOR FLUX LOCUS STRATEGY FOR ENHANCING TORQUE CONTROL IN HIGH-SPEED INDUCTION MOTORS

Syed Abrar Bin Syed Ahmad Zawawi

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SYED ABRAR BIN SYED AHMAD ZAWAWI

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DECLARATION

I declare that this thesis entitled “Hybrid Stator Flux Locus Strategy For Enhancing Torque Control In High-Speed Induction Motors “ is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :.....

Name : Syed Abrar Bin Syed Ahmad Zawawi

Date : 18 June 2025

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering

Signature : .....

Supervisor Name : Dr. Auzani Bin Jidin

Date : 18 June 2025

DEDICATION

I would like to express my deepest appreciation and heartfelt gratitude to my beloved family my father, Syed Ahmad Zawawi, my mother, Hashida, and my siblings for their unwavering financial and emotional support throughout the course of my master's studies at Universiti Teknikal Malaysia Melaka (UTeM). I am also sincerely thankful to my dear friends for their encouragement, assistance, and contributions to this project. Their support has been invaluable, and this achievement would not have been possible without them. Thank you.

ABSTRACT

This thesis presents an enhanced Direct Torque Control (DTC) strategy for three-phase induction motors aimed at improving dynamic torque control performance in high-speed operations by modifying the stator flux locus. DTC is widely adopted in industrial applications due to its simple structure and fast torque response. However, it suffers from notable limitations such as high torque ripple and inadequate torque control under high-speed conditions. These drawbacks are primarily due to the use of hysteresis controllers and the limitation imposed by a circular stator flux locus, which restricts the angular frequency of the stator flux vector and degrades the ability to maintain the load angle, thus reducing torque control effectiveness at high speeds. To overcome the poor torque dynamic control performance at high speeds, this research proposes a simple modification of the stator flux locus from a circular into a hexagonal by adjusting the flux hysteresis bandwidth with an appropriate bandwidth. A hybrid control of flux locus is proposed where the hexagonal flux locus is controlled during the dynamic conditions (acceleration and a sudden large torque demands), while the circular flux locus is controlled during steady-state conditions (constant speed and torque demands). By modifying the flux locus into a hexagonal shape, the angular velocity of the stator flux vector can be increased beyond its conventional limit, thereby maintaining the load angle and hence the motor torque at high speeds. This approach also promotes the application of the most optimal voltage vectors (the voltage vectors that have the largest tangential component) to the stator flux vector are frequently applied and this enables the transition of phase voltages from a PWM to almost a six-step voltage in satisfying the torque demand, during acceleration mode. On the other hand, the flux locus transforms back to a circular locus which retains lower current harmonic distortions when the speed reaches to its demand (steady-state condition). The hybrid flux locus control strategy is adopted in the simple DTC structure where the mechanism to modify the flux locus is enabled when the DTC applied the hexagonal` bandwidth and detects a dynamic condition when a large speed error is detected. Simulation and experimental results confirm performance gains, including a 31.25% faster dynamic response, elimination of steady-state speed error by 3.57%, and a 16.7% reduction in steady-state operating current. The benefit of this research is the improvements can be achieved without the use of complex flux weakening and space vector modulation (SVM) strategy, making the approach a practical and scalable solution for high-performance industrial drives and electric vehicle applications.

PENGUBAHSUAIAN LOKUS FLUKS STATOR UNTUK PENAMBAHBAIKAN KAWALAN TORK DALAM MOTOR ARUHAN BERKELAJUAN TINGGI

ABSTRAK

Tesis ini membentangkan strategi Kawalan Torsi Langsung (DTC) yang dipertingkat untuk motor aruhan tiga fasa yang bertujuan meningkatkan prestasi kawalan torsi dinamik dalam operasi berkelajuan tinggi melalui pengubahsuaian lokus fluks stator. DTC digunakan secara meluas dalam aplikasi industri disebabkan oleh strukturnya yang ringkas dan tindak balas torsi yang pantas. Walau bagaimanapun, ia mempunyai batasan ketara seperti riak torsi yang tinggi dan kawalan torsi yang tidak mencukupi di bawah keadaan kelajuan tinggi. Kelemahan ini berpunca daripada penggunaan pengawal histeresis dan batasan yang dikenakan oleh lokus fluks stator bulat, yang menyekat frekuensi sudut vektor fluks stator dan mengurangkan keupayaan untuk mengekalkan sudut beban, seterusnya mengurangkan keberkesanan kawalan torsi pada kelajuan tinggi. Untuk mengatasi prestasi kawalan torsi dinamik yang lemah pada kelajuan tinggi, penyelidikan ini mencadangkan pengubahsuaian mudah lokus fluks stator daripada bulat kepada heksagon dengan melaraskan lebar jalur histeresis fluks dengan lebar jalur yang sesuai. Kawalan hibrid lokus fluks dicadangkan di mana lokus fluks heksagon dikawal semasa keadaan dinamik (contohnya, pecutan dan permintaan torsi besar secara tiba-tiba), manakala lokus fluks bulat dikawal semasa keadaan mantap (contohnya, kelajuan malar dan permintaan torsi). Dengan mengubahsuai lokus fluks kepada bentuk heksagon, halaju sudut vektor fluks stator boleh ditingkatkan melebihi had konvensionalnya, seterusnya mengekalkan sudut beban dan dengan itu torsi motor pada kelajuan tinggi. Pendekatan ini juga menggalakkan aplikasi vektor voltan paling optimum (iaitu vektor voltan yang mempunyai komponen tangen terbesar) kepada vektor fluks stator digunakan dengan kerap dan ini membolehkan peralihan voltan fasa daripada PWM kepada voltan hampir enam langkah dalam memenuhi permintaan torsi, semasa mod pecutan. Sebaliknya, lokus fluks berubah kembali kepada lokus bulat yang mengekalkan distorsi harmonik arus yang lebih rendah apabila kelajuan mencapai permintaannya (iaitu keadaan mantap). Strategi kawalan lokus fluks hibrid digunakan dalam struktur DTC ringkas di mana mekanisme untuk mengubahsuai lokus fluks diaktifkan apabila DTC menggunakan lebar jalur hexagonal dan mengesan keadaan dinamik apabila ralat kelajuan melebihi dikesan. Keputusan simulasi dan eksperimen mengesahkan peningkatan prestasi, termasuk tindak balas dinamik 31.25% lebih pantas, penghapusan ralat kelajuan keadaan mantap sebanyak 3.57%, dan pengurangan 16.7% dalam arus operasi keadaan mantap. Manfaat penyelidikan ini ialah penambahbaikan boleh dicapai tanpa menggunakan strategi pelemahan fluks dan modulasi vektor angkasa (SVM) yang kompleks, menjadikan pendekatan ini sebagai penyelesaian praktikal dan skalabel untuk pemacu industri berprestasi tinggi dan aplikasi kenderaan elektrik.

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LIST OF ABBREVIATIONS

DC	-	Direct Current
AC	-	Alternating Current
UTeM	-	Universiti Teknikal Malaysia Melaka
FOC	-	Field-Oriented Control
DTC	-	Direct Torque Control
SVM	-	Space Vector Modulation
VFDs	-	Variable Frequency Drives
EMI	-	Electromagnetic Interference
VSI	-	Voltage Source Inverter
IGBTs	-	Insulated Gate Bipolar Transistors
IM	-	Induction Motor
UB	-	Upper Band
LB	-	Lower Band
MB	-	Middle Band
PI	-	Proportional-Integral
VSC	-	Variable-Structure Control
FPGAs	-	Field Programmable Gate Arrays
CSF	-	Constant Switching Frequency
PWM	-	Pulse Width Modulation
Sec	-	Sector
ENC	-	Encoder
DAC	-	Digital-to-Analog Converter

ADC	-	Analog-to-Digital Converter
I/O	-	Input/Output
IE	-	Incremental Encoder
V	-	Voltage
HP	-	Horsepower
RPM	-	Revolution per minutes

LIST OF SYMBOLS

$\bar{v}_s$	-	Stator voltage space vectors
R_s	-	Stator resistance
i_s	-	Stator current space vectors
$\bar{\varphi}_s$	-	Stator flux
$\bar{v}_r$	-	Rotor voltage
R_r	-	Rotor voltage
i_r	-	Rotor current
φ_r	-	Rotor flux
ω_r	-	Rotor electrical speed
L_s	-	Stator self-inductances
L_r	-	Rotor self-inductances
L_m	-	Mutual inductance
T_e	-	Electromagnetic torque
P	-	Number of pole pairs
s	-	Laplace operator
S_x	-	Upper switch
$\bar{S_x}$	-	Lower switch
$\bar{v}_x$	-	Voltage vectors
δ_{sr}	-	Load angle
δ_{sr0}	-	Initial load angle
σ_T	-	Torque error status
V_{DC}	-	DC voltage

t	-	Time
q	-	q-axis
d	-	d-axis
φ_s^*	-	Stator flux reference
φ_s	-	Stator flux
φ_{err}	-	Flux error
σ_φ	-	Flux error status
ε_T	-	Torque error
T_e^*, $T_{e,\,reff}$	-	Torque reference
T_e	-	Torque
Nm	-	Newton meter
DT	-	Sampling time
T	-	Period
k_p	-	Proportional gain
k_i	-	Integral gain
c_{upper}	-	Upper carrier
c_{lower}	-	Lower carrrier
E_ω	-	Speed error
θ_φ	-	Flux angle
ω_m	-	Motor speed
ω_{ref}	-	Speed Reference
N	-	Motor speed in rpm
T_s	-	Sampling time

ppr - Pulses per revolution

LIST OF APPENDICES

LIST OF PUBLICATIONS

The following is a list of publications derived from the research conducted in this thesis:

S.A.S.A. Zawawi, A. Jidin, N.S.M. Sabri, S.A.A. Tarusan, 2025. Enhanced torque control in high-speed DTC using modified stator flux locus. *International Journal of Power Electronics and Drive Systems*, 16(1), pp. 457–463. (Scopus)

N.S.M. Sabri, S.A.A. Tarusan, S.A.S.A. Zawawi, A. Jidin, T. Sutikno, 2025. Optimizing low-speed DTC performance for three-phase induction motors with sector rotation strategy. *International Journal of Power Electronics and Drive Systems*, 16(1), pp. 464–471. (Scopus)

N.S.M. Sabri, S.A.A. Tarusan, S.A.S.A. Zawawi, A. Jidin, 2025. Mitigating Flux Droop in Low-Speed Steady-State DTC for Three-Phase Induction Motors. *2025 IEEE 8th International Conference on Electrical, Control and Computer Engineering (InECCE)*. 27 August 2025 IEEE, pp. 171–176. (Scopus)